Thermal Radiation from Au + Au Collisions at $\sqrt{s_{NN}} = 200$ GeV Energy

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Abstract. The transverse momentum distribution of the direct photons measured by the PHENIX collaboration in $Au + Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV/A has been analyzed. It has been shown that the data can be reproduced reasonably well assuming a deconfined state of thermalized quarks and gluons with initial temperature more than the transition temperature for deconfinement inferred from lattice QCD. The value of the initial temperature depends on the equation of state of the evolving matter. The sensitivities of the results on various input parameters have been studied. The effects of the modifications of hadronic properties at non-zero temperature have been discussed.

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1. Introduction

Study of photon spectra emanating from hot and dense matter formed in ultra-relativistic heavy ion collisions is a field of considerable current interest. Electromagnetic probes have been proposed to be the promising tools to characterize the initial state of the collisions [1, 2, 3, 4, 5]. Because of the very nature of their interactions photons and dileptons suffer minimum rescattering and therefore, can be used as efficient tools to extract the initial temperature of the system. By comparing the initial temperature with the transition temperature estimated from lattice QCD, one can infer whether Quark Gluon Plasma (QGP) is formed or not.

On the experimental side substantial progress has been made in measuring the transverse momentum spectrum of photons from nuclear collisions at Super Proton Synchrotron (SPS) [6] and Relativistic Heavy Ion Collider (RHIC) [7]. In contrast to the earlier results [7] PHENIX collaboration has analyzed the data by using a novel technique and reported [8] excess direct photons over the next to leading order perturbative QCD (NLO pQCD) processes for $Au+Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV. The corresponding theoretical analysis of the data presented in Ref. [7] was performed in Ref. [9]. The purpose of the present work is to analyze the new experimental data and infer the initial temperature of the system formed after the collisions. The sensitivity of the results on various input parameters *e.g.* transition temperature, strong coupling constant, equation of states etc have been presented.

The paper is organized as follows. In the next section the photon production rates from QGP and hot hadronic gas are discussed. The photons are produced from various reactions and decays taking place in an expanding medium. Therefore, the static (fixed temperature) emission rates should be convoluted with the space time evolution of the system. The space time evolution of the system is outlined in section 3. Results of the calculations are presented in section 4. Section 5 is devoted for summary and discussions.

2. Photon spectra

Let us identify the possible sources of “excess” photons above those coming from the decays of π^0, η mesons etc. as provided by the data. Photons from the decays of π^0, η etc. are subtracted from the data and hence will not be discussed here. For the transverse momentum spectra of the photon, first we focus on the high p_T domain. These are populated by the prompt photons originating from the hard collisions of initial state partons in the colliding nuclei. This is believed to be the domain where contributions can be estimated by pQCD. We use NLO predictions by Gordon and Vogelsang [10] from pp collisions and scale it up by the number of binary collisions for $Au+Au$ interactions to obtain the prompt contributions to the direct photons. It should be noted here that NLO prediction does not require any intrinsic k_T smearing to explain the $p-p$ data [11]. This effect is ignored in the analysis of $Au+Au$ data in the present work. The fast quarks propagating through QGP lose energy due to gluon

radiation and hence produce photons with reduced energy via fragmentation processes. This indicates that photon production by these processes will be suppressed. However, the induced emission of photons by the hard partons due to multiple scattering in the QGP will enhance the photon radiation. It is shown in Ref. [12] that the enhancement due to induced radiation compensates the suppression due to jet energy loss for the p_T domain considered here. Therefore, we ignore these mechanisms in the current analysis. Photon production from the interaction of thermal gluons and non-thermal quarks was first considered in [13] within the framework of Fokker Planck equation. Contributions from the hard partons undergoing annihilation and Compton processes with the quarks and gluons in the thermal medium [14] have been evaluated and its importance has been highlighted recently. Discussions on these contributions are beyond the scope of the present work (see [15] for further details). The duration of the pre-equilibrium stage will be small because thermalization time taken here is small (~ 0.2 fm) and hence the contributions from this stage may be small. Photons from the pre-equilibrium stage and hard-thermal conversion are neglected here. The fact that the current experimental data can be explained without these contributions indicate that theoretical uncertainties exist at present.

The estimation of the thermal contribution depends on the space-time evolution scenario that one considers. In case of a deconfinement phase transition, which seems to be plausible at RHIC energies (see [16] for a review), one assumes that QGP is formed initially. The equilibrated plasma then expands, cools, and reverts back to hadronic matter and finally freezes out at a temperature ~ 120 MeV. Evidently there will also be thermal radiation from the luminous hadronic fireball which has to be evaluated properly in order to have a reliable estimate of the initial temperature.

The photon emission rate from QGP due to Compton ($q(\bar{q})g \rightarrow q(\bar{q})\gamma$) and annihilation ($q\bar{q} \rightarrow g\gamma$) processes was evaluated [17, 18] by using Hard Thermal Loop (HTL) approximation [19]. Later it was shown [20] that photon production from the reactions, $gq \rightarrow gq\gamma$, $qq \rightarrow qq\gamma$, $qq\bar{q} \rightarrow q\gamma$ and $gq\bar{q} \rightarrow g\gamma$ contribute in the same order as annihilation and Compton processes. However, this calculation does not incorporate suppression due to multiple scattering during the emission process. This point was later clarified in Ref. [21]. The complete calculation of photon emission rate from QGP to order α_s has been completed by resuming ladder diagrams in the effective theory [22]. We use the results of Ref. [22] in the present work. The parameterizations of the emission rates for various processes are available in Ref. [23]. The temperature dependence of the strong coupling constant is taken from Ref. [24].

While evaluating the photons from hadronic phase we consider an exhaustive set of hadronic reactions and the radiative decay of higher resonance states [25, 26, 27, 28]. The relevant reactions and decays for photon productions are: (i) $\pi\,\pi \rightarrow \rho\,\gamma$, (ii) $\pi\,\rho \rightarrow \pi\gamma$ (with π, ρ, ω, ϕ and a_1 in the intermediate state [27]), (iii)$\pi\,\pi \rightarrow \eta\,\gamma$ and (iv) $\pi\,\eta \rightarrow \pi\,\gamma$, $\rho \rightarrow \pi\,\pi\,\gamma$ and $\omega \rightarrow \pi\,\gamma$. The corresponding vertices are obtained from various phenomenological Lagrangians described in detail in Ref. [25, 26, 27, 28]. Contributions from other decays, such as $K^*(892) \rightarrow K\,\gamma$, $\phi \rightarrow \eta\,\gamma$, $b_1(1235) \rightarrow \pi\,\gamma$,

$a_2(1320) \rightarrow \pi\gamma$ and $K_1(1270) \rightarrow \pi\gamma$ have been found to be small [29] for $p_T > 1$ GeV. All the isospin combinations for the above reactions and decays have properly been taken into account.

Various experiments suggest that the spectral functions of hadrons are modified in a dense nuclear environment [30, 31, 32, 33, 34, 35, 36]. The enhancement of lepton pair yield in CERES data [37] below the ρ-mass can only be explained by assuming the in-medium modifications of the ρ meson [38, 39, 40, 41]. The photon spectra measured by WA98 collaboration at CERN-SPS energies have been reproduced by assuming the reduction of hadronic masses in the thermal bath [42, 43]. It was shown in Ref. [43] that the p_T distribution of photons changes significantly with a reduced mass scenario and is almost unaffected by the broadening [43] of the vector meson spectral function in the medium. On the other hand the invariant mass distribution of the lepton pairs is sensitive to both the reduction in vector meson masses [39, 40] as well as the enhanced width of the vector mesons [38, 41]. Thus, by looking only at the dilepton spectra, it is difficult to differentiate the above scenarios. We need to analyze both the photon and dilepton spectra simultaneously.

There is no consensus on the nature of the vector meson modification in matter - pole shift or broadening - both experimentally [33, 34, 35, 36] and theoretically [38, 44]. The shift in hadronic spectral function depends on the temperature and (baryonic) chemical potential of the thermal bath created after the collisions. The value of baryonic chemical potential for system produced after the collision at $\sqrt{s_{NN}} = 200$ GeV is much smaller [16] compared to the other lower energy collisions [45]. Therefore, the extrapolation of the nature of change observed in these low energy experiments to RHIC energy may suffer from various uncertainties, because for matter formed at RHIC collision the net baryon number is very small (baryon - anti-baryon ~ 0). Because of these reasons and the insensitivities of photon spectra on broadening we consider the reduction of hadronic masses to evaluate photon productions from hadronic matter to estimate T_i. The nature of changes in the hadronic spectral function at non-zero temperature and density is not known from first principle at present. Thus one has to rely on calculations based on various phenomenological models (see [5, 38, 46] for a review).

In the present work we use Brown-Rho (BR) scaling scenario [47] (see also [48]) for in-medium modifications of hadronic masses (except pseudoscalars). BR scaling has been used here to indicate how far the value of initial temperature is affected when the reduction of the hadronic mass is incorporated in evaluating the photon spectra. The BR scaling indicates stronger reduction of hadronic masses as compared to Quantum Hadrodynamics (QHD) [49]. As the abundances of hadrons increase with the reduction in their masses, photon yield is expected to increase from hadronic phase with BR scaling. Therefore, in this scenario a conservative estimate of the photons from QGP phase and hence a conservative value of the initial temperature is obtained. In this article, we do not discuss the details about the computational procedure as this has been done in Refs. [5, 25, 26, 42, 43].

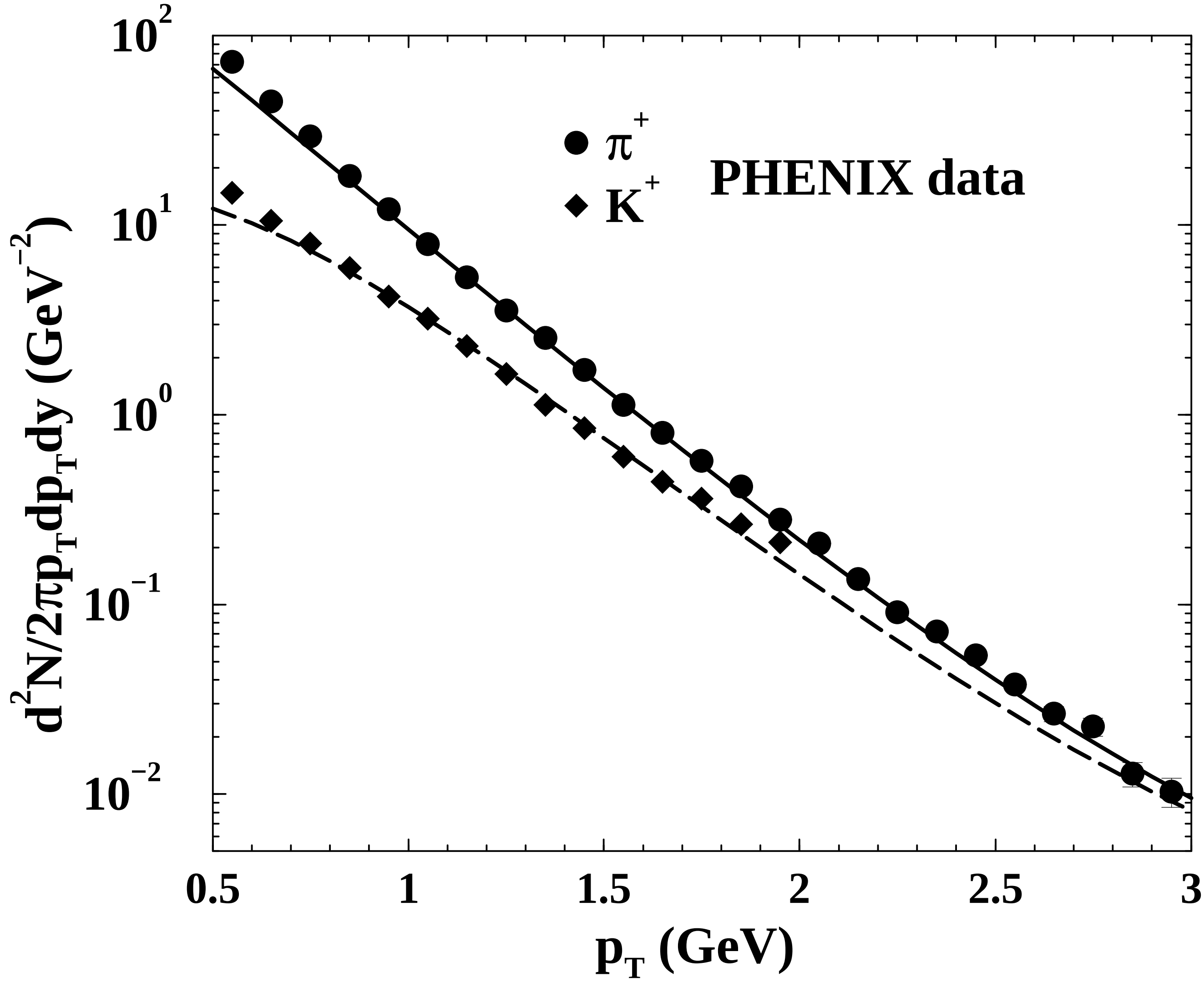

Figure 1. π^+ (circle) and K^+ (diamond) spectra at $\sqrt{s_{NN}} = 200$ GeV measured by PHENIX Collaboration. Solid (dashed) line depicts the pion (kaon) spectra obtained in the hydrodynamical model. The data is taken from [59] for Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV for $(0-5)\%$ centrality. Type I EOS has been here with $T_i = 400$ MeV, $\tau_i = 0.2$ fm and $T_f = 120$ MeV.

3. Space time evolution

The ideal relativistic hydrodynamics in (2+1)D [50] with longitudinal boost invariance [51] and cylindrical symmetry has been used for the space time evolution.

3.1. initial condition

In case of isentropic expansion the experimentally measured hadron multiplicity can be related to the initial temperature and thermalization time by the following equation [52]:

$$T_i^3(b)\tau_i = \frac{2\pi^4}{45\zeta(3)\pi\, R_A^2 4a_k}\frac{dN}{dy}(b) \tag{1}$$

where $dN/dy(b)$ is the hadron (predominantly pions) multiplicity for a given impact parameter b, R_A is the radius of the system, τ_i is the initial thermalization time, $\zeta(3)$ is the Riemann zeta function and $a_k = (\pi^2/90)\, g_k$ is the degeneracy of the system created. The hadron multiplicity resulting from $Au + Au$ collisions is related to that from pp collision at a given impact parameter and collision energy by

$$\frac{dN}{dy}(b) = [(1-x)N_{part}(b)/2 + xN_{coll}(b)]\,\frac{dN_{pp}}{dy} \tag{2}$$

where x is the fraction of hard collisions. N_{part} is the number of participants and N_{coll} is the number of collisions evaluated by using Glauber model. $dN_{pp}^{ch}/dy = 2.5 - 0.25ln(s) + 0.023ln^2 s$, is the multiplicity of the produced hadrons in pp collisions at centre of mass energy, $\sqrt{s}$ [53]. We have assumed that 25% hard (i.e. $x = 0.25$)and 75% soft collisions are responsible for initial entropy production.

We further assume that the system is formed in a thermalized phase of quarks and gluons at the initial thermalization time $\tau_i = 0.2$ fm. Taking the number of flavours, $N_F = 2.5$, $dN/dy \sim 1100$ and solving Eq. 1 the value of the initial temperature (T_i) is obtained as $T_i = 400$ MeV. The initial energy density and radial velocity profiles are taken as:

$$\epsilon(\tau_i, r) = \frac{\epsilon_0}{1 + e^{(r-R_A)/\delta}} \tag{3}$$

and

$$v(\tau_i, r) = v_0\left[1 - \frac{1}{1 + e^{(r-R_A)/\delta}}\right] \tag{4}$$

Sensitivities of the results on the velocity profiles will be shown, δ (~ 0.5 fm here) is a parameter, known as the surface thickness. Unless mention explicitly the initial radial velocity is taken as zero.

3.2. Equation of state (EOS)

Apart from the initial conditions, we also need the EOS to solve the hydrodynamic equations. Ideally the EOS should be obtained from the first principle *i.e.* within the framework thermal QCD. Although, these results has large uncertainties for temperature $\leq T_c$ because the pseudoscalar mass is large [54], we have used it here to find out the conservative value of T_i. Therefore, two types of equation of state will be used here to study the photon spectra to indicate the sensitivity of the results.

(I) Bag model type EOS has been used for QGP. For EOS of the hadronic matter all the resonances with mass < 2.5 GeV $/c^2$ has been considered. The velocity of sound

is taken as $c_s^2 = 1/3$ and $1/5$ [55] for QGP and hadronic phase respectively. The effect of baryonic chemical potential is neglected here.

(II) EOS from lattice QCD [56] has also been used here to show the sensitivity of our results on the equation of state and to find out the conservative value of T_i.

The transition temperature is taken as $T_c \sim 190$ MeV as obtained from lattice QCD [57, 58] recently. However, the sensitivity of the results on T_c will also be demonstrated. The freeze-out temperature, T_f has been fixed by studying the transverse momentum distribution of hadrons.

4. Results

First we use the type I EOS and initial conditions described above to solve the relativistic hydrodynamic equations for studying the p_T spectra of pions and kaons. To reproduce the transverse momentum distribution of pions and kaons (Fig. 1) measured experimentally by PHENIX collaboration [59], the required value of $T_f \sim 120$ MeV. In all the results shown below the value of the freeze-out temperature is fixed at 120 MeV. The dependence of the p_T distributions of hadrons on the initial temperature is rather weak for the p_T values under consideration. It is assumed here that the chemical equilibrium is maintained up to T_f. A comment on the chemical freeze-out temperature is in order here. Depending upon the scenarios (see below) considered here, the value of the initial temperatures are 400 MeV and 590 MeV, which are quite high. Because of the high initial temperatures the photon emission from the early stage dominate over the contributions from the late stage of the evolution. This is in agreement with the results obtained in [60] at lower (SPS) energies. Moreover, it is also shown in [60] that results from ideal hydrodynamics and coarse grained UrQMD are in reasonable agreement. Therefore, photon spectra will not be affected significantly if chemical equilibrium is not maintained in the late stage of the evolution. The effect of finite baryonic chemical potential on the production rate of photon from an equilibrated QGP is also small [61].

Now we concentrate on the transverse momentum spectra of photons. The resulting spectra is contrasted with the recent PHENIX measurements of direct photons in Fig. 2. We observe that the data is reproduced with $T_i = 400$ MeV and $\tau_i = 0.2$ fm with in-medium modification of hadrons and type I EOS. It is found that the contributions from quark matter and hadronic matter to the photon production are similar in the p_T interval, $1 \leq p_T(\mathrm{GeV}) \leq 3$, the range where thermal contribution dominates.

In Ref. [9] the initial temperature and thermalization time are taken as 590 MeV and 0.15 fm respectively to evaluate the photon spectra. They have used the hadronic photon production rates of Ref. [62]. We reproduce the photon spectra with this initial condition by using the hadronic emission rates of photons from [25, 26, 27, 28]. As in Ref. [9] the medium effects are neglected in this case. The resulting photon spectrum is also shown in Fig. 2 for comparison. If we fix $\tau_i = 0.15$ fm then the data can also be described reasonably well for $T_i = 440$ MeV (keeping $T_i^3\tau_i \propto dN/dy$ fixed) if the medium effects on hadrons are taken into account. It may be mention here that photons

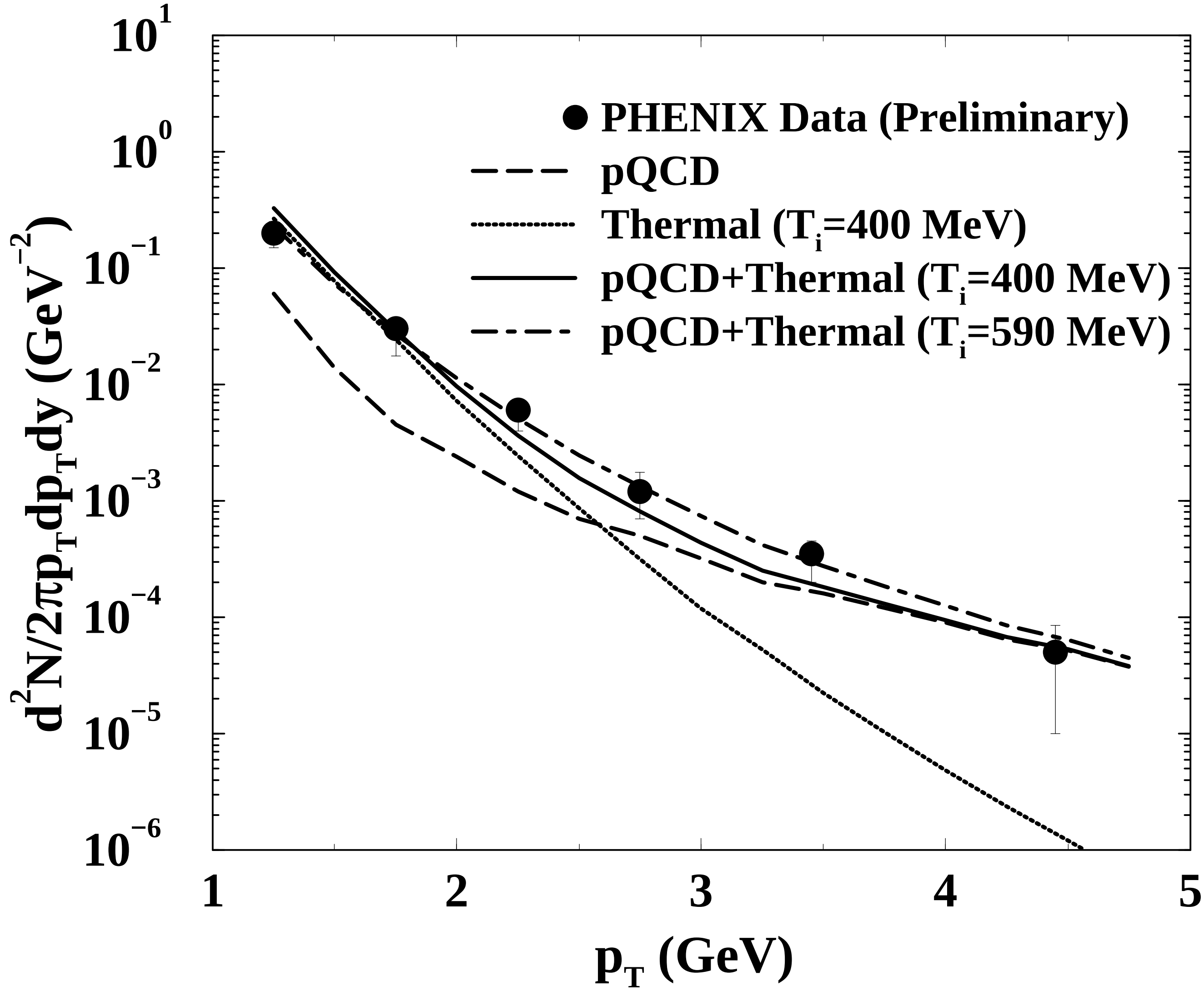

Figure 2. Direct photon spectra at RHIC energies measured by PHENIX Collaboration for $(0-20)\%$ centrality. Dashed line indicates hard photons from NLO pQCD calculations [10]. Solid (dot-dashed) line depicts the total photon yield obtained from QGP initial state with $T_i = 400$ MeV and $\tau_i = 0.2$ fm ($T_i = 590$ MeV $\tau_i = 0.15$ fm). Type I EOS has been used to obtain the thermal contributions shown in this figure. In medium effects on hadrons are included (ignored) in the results shown by solid (dot-dashed) line. Photon production rate from QGP is taken from [22].

from strange hadrons [62] is down by a factor of 2 (at $p_T \sim 2$ GeV) compared to the production rates from nonstrange hadrons (π, $\rho\,\omega$, η). The contributions involving η mesons are neglected in Ref. [62].

As mentioned earlier the reduction of hadronic masses in a thermal bath increases their abundances and hence the rate of photon emission gets enhanced [5, 25, 26]. As a result a smaller initial temperature compared to the one obtained in Ref. [9], is seen to reproduce the data reasonably well. The variation of hadronic masses with temperature

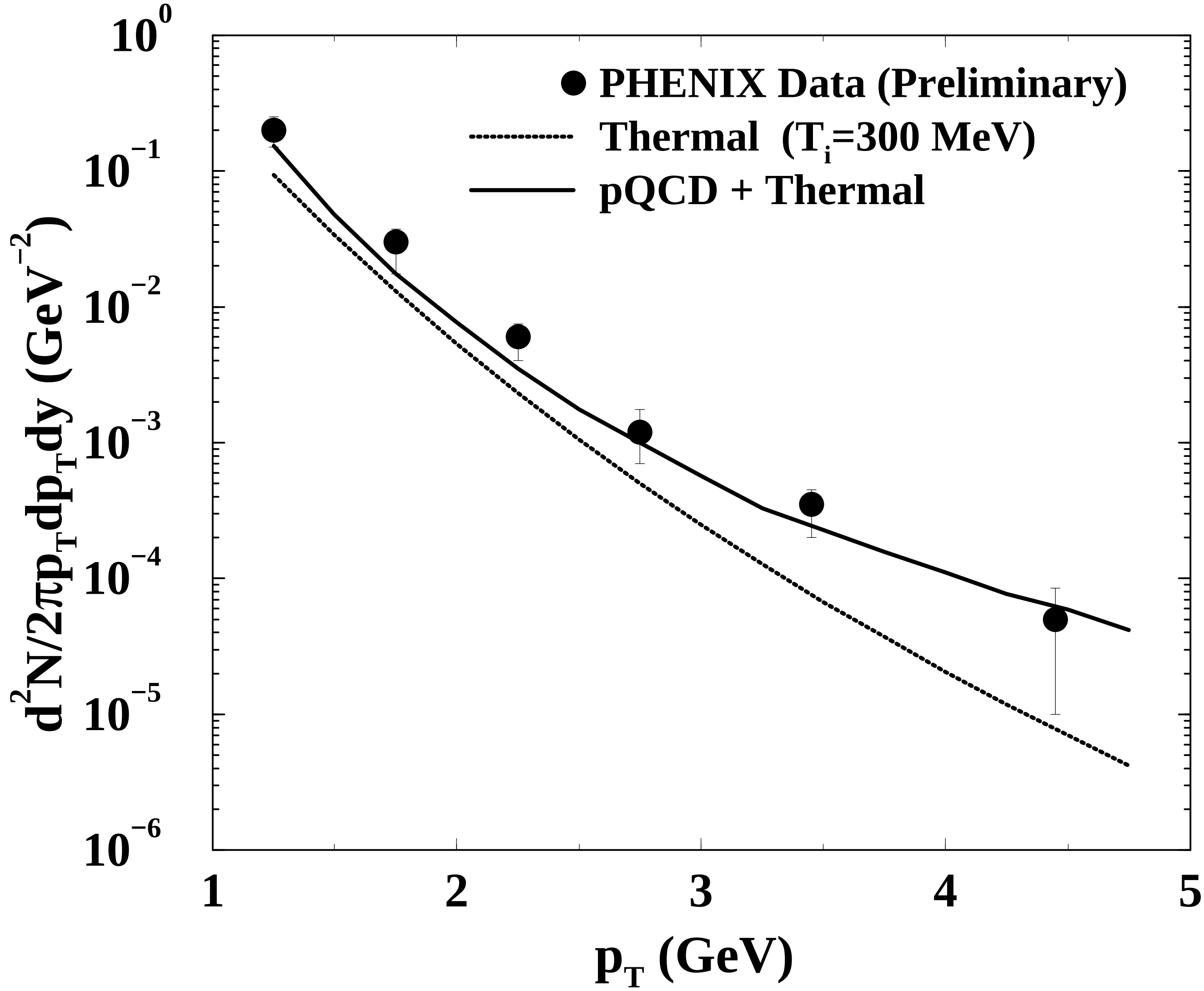

Figure 3. Same as Fig. 2 for type II EOS, with $T_i = 300$ MeV, $\tau_i = 0.5$ fm and $T_f = 120$ MeV. Photon production rate from QGP is taken from [22].

in QHD model [5, 49] is slower than the BR scaling. As a result the PHENIX photon data requires higher value of T_i in QHD than BR scaling scenario. Hence to pinpoint the actual initial temperature through photon spectra it is imperative to understand the properties of hadrons in hot and dense environment. However, it is clear that the initial temperature obtained in the present analysis is more than the value of T_c obtained from lattice QCD calculations.

The initial temperature obtained from the analysis of the RHIC data is ~ 400 MeV in the present work and ~ 590 MeV in [9]. This may be compared with the value of the initial temperature obtained from the analysis of SPS data. The value of initial temperature obtained from the analysis of the single photon data from Pb + Pb collisions at SPS [6] is within the range $\sim 200-230$ MeV [42, 43, 63, 64, 65, 66]. A

much higher value of $T_i \sim 335$ MeV is obtained in [67] by assuming a very small value of $\tau_i \sim 0.2$ fm for SPS energy.

To show the sensitivity of the results on the EOS we evaluate the photon spectra using type II EOS (lattice QCD) in hydrodynamical evolution. It is seen (Fig. 3) that the data can be reproduced with lower initial temperature, $T_i \sim 300$ MeV (and hence larger thermalization time scale ~ 0.5 fm). This is so because in the case of type II EOS the space time evolution of the system for temperature below the transition temperature is slower than type I EOS. Hence the hadronic phase live longer for type II EOS, radiating more photons from this phase. However, it should be mentioned here that the slope of the p_T spectra of hadrons can not be reproduced by type II EOS with the value of the freeze-out temperature mentioned above.

It may be mentioned at this point that the photon emission rates obtained in [22] are valid in weak coupling limit, although the QGP formed after $Au + Au$ collisions at RHIC energy could be strongly coupled[68]. However, photon production from strongly coupled QGP is not available from thermal QCD. Therefore, results in strong coupling limit would be useful even if it comes from a theory which is not real QCD. Recently, results from $\mathcal{N} = 4$ Supersymmetric Yang Mills (SYM) theory have been made available [69, 70] in the strong coupling limit. The rate obtained in this case could be treated as a upper limit of photon production from QGP. The thermal photons obtained in this case are compared with that from thermal QCD in Fig. 4. Photons from SYM is enhanced by about 20% as compared to thermal QCD in the p_T region ~ 2 GeV.

When the results obtained from SYM is added with thermal photons from hadronic phase and photons from pQCD it describes the data reasonably well (see Fig. 5). The initial temperature and time are taken as 300 MeV and 0.5 fm respectively. The type II EOS is used here. It should be mentioned here that for type I EOS and production rate from SYM, $T_i \sim 400$ MeV and $\tau_i \sim 0.2$ fm is required to reproduce the data.

In Fig. 6 the dependence of photon spectra from QGP phase on strong coupling is demonstrated. The temperature dependence of α_s has been taken from [24]. The difference in photon spectra at $p_T \sim 3$ GeV for $\alpha_s = 0.3$ and temperature dependent α_s is about 13%.

A 20% enhancement is obtained at $p_T \sim 2$ GeV in total thermal photon production if transition temperature is increased from 170 to 190 MeV (Fig. 7). Photons from hadronic phase populate mainly the low p_T region of the spectra. Larger value of transition temperature means that hadrons survive up to larger temperature and emit more photons at low p_T region.

All the results presented above are obtained with vanishing initial radial velocity *i.e.* for $v_0 = 0$ in Eq. 4. Finally, we demonstrate the sensitivity of results on the value and shape of the initial velocity profile. In Fig. 8 we show the results for $v_0 = 0$ (solid line) and $v_0 = 0.2$ (dashed line) in Eq. 4. The difference in results is rather small. However, for a different velocity profile, $v_r(\tau_i, r) = v_0^1\, r/R_A$ a substantial change in the spectra is observed for $v_0^1 = 0.2$, because this gives a stronger radial velocity distribution of the fluid compared to Eq. 4. It will be interesting to put constrains on the initial velocity

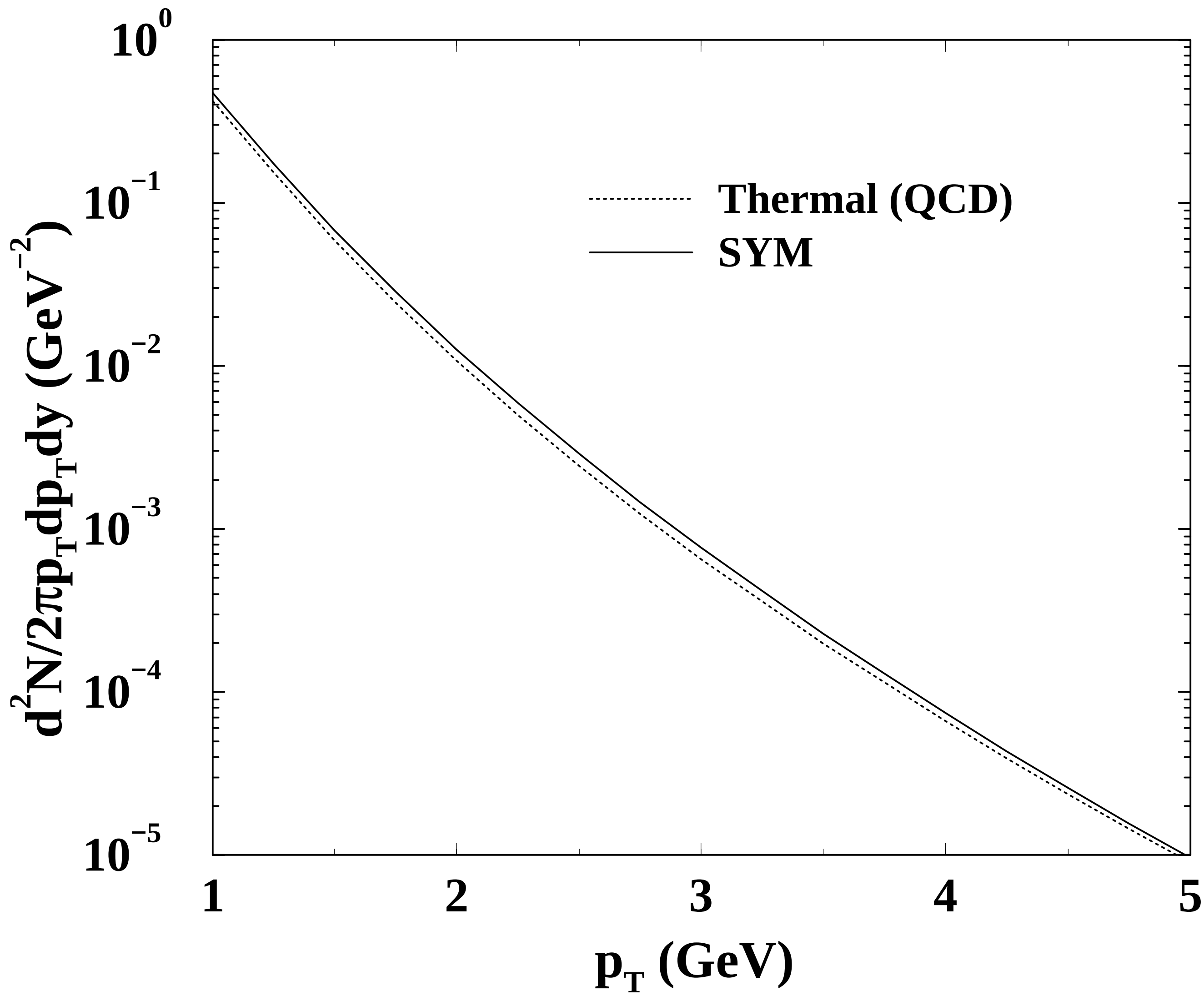

Figure 4. Solid (dotted) represents p_T spectra of thermal photons when photons from QGP is evaluated within the ambit of SYM theory (thermal QCD). The values of $T_i = 590$ MeV, $\tau_i = 0.15$ fm and $T_f = 120$ MeV. Type II EOS has been used here.

profile from experimental data on the p_T distributions of various types of hadrons [71].

5. Summary and Discussions

In summary, we have analyzed the direct photon data measured by PHENIX collaboration for $Au + Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV. The data can be reproduced by assuming a deconfined state of quarks and gluons with initial temperature ~ 400 MeV. However, for type II EOS the data can be explained for lower value of $T_i \sim 300$ MeV. Since the type II EOS fails to reproduce the slope of the p_T distributions of pions and kaons as mentioned earlier, this value of T_i should be taken with caution. The type I EOS considered here is similar to EOS Q of ref. [72]. EOS H of [72] (hadronic

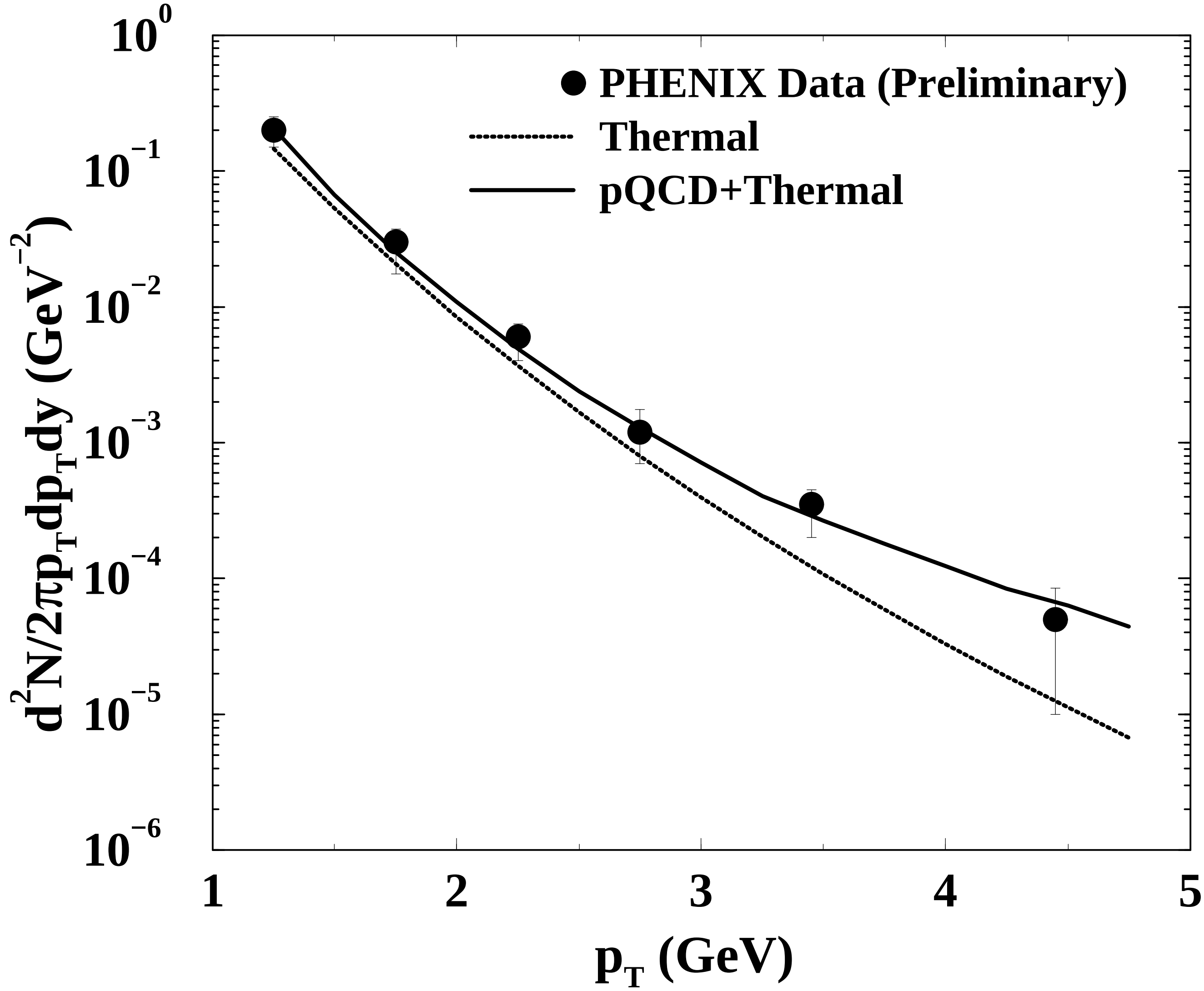

Figure 5. Direct photon spectra at RHIC energies measured by PHENIX Collaboration. Solid (dotted) line depicts the pQCD + thermal (thermal) photon yield. Thermal photons from QGP phase is obtained from SYM theory [22]. Here T_i = 300 MeV and $\tau_i = 0.5$ fm. Type II EOS is used to obtain the thermal contributions.

scenario without any phase transition) has not been considered here, because we feel this scenario is not realistic at RHIC collision at $\sqrt{s_{NN}} = 200$ GeV. The other EOS, thermal quasi-particle model considered in [73] gives T_i more than 300 MeV. Therefore, $T_i = 300$ MeV obtained here for type II EOS is the conservative lower limit. Photon productions from thermal QCD and $\mathcal{N} = 4$ SYM have been compared to the data. In both the cases similar values of the initial temperatures are obtained. The extracted average temperature (T_{av}) from the slope of the photon (p_T) spectra is found to be ~ 265 MeV for the p_T range between 1.25 to 2.25 GeV where thermal contributions dominate. When the effects of flow is ignored (by putting $v_r = 0$ for all time) the 'true' average temperature is found to be 215 MeV. The initial temperature must be more than

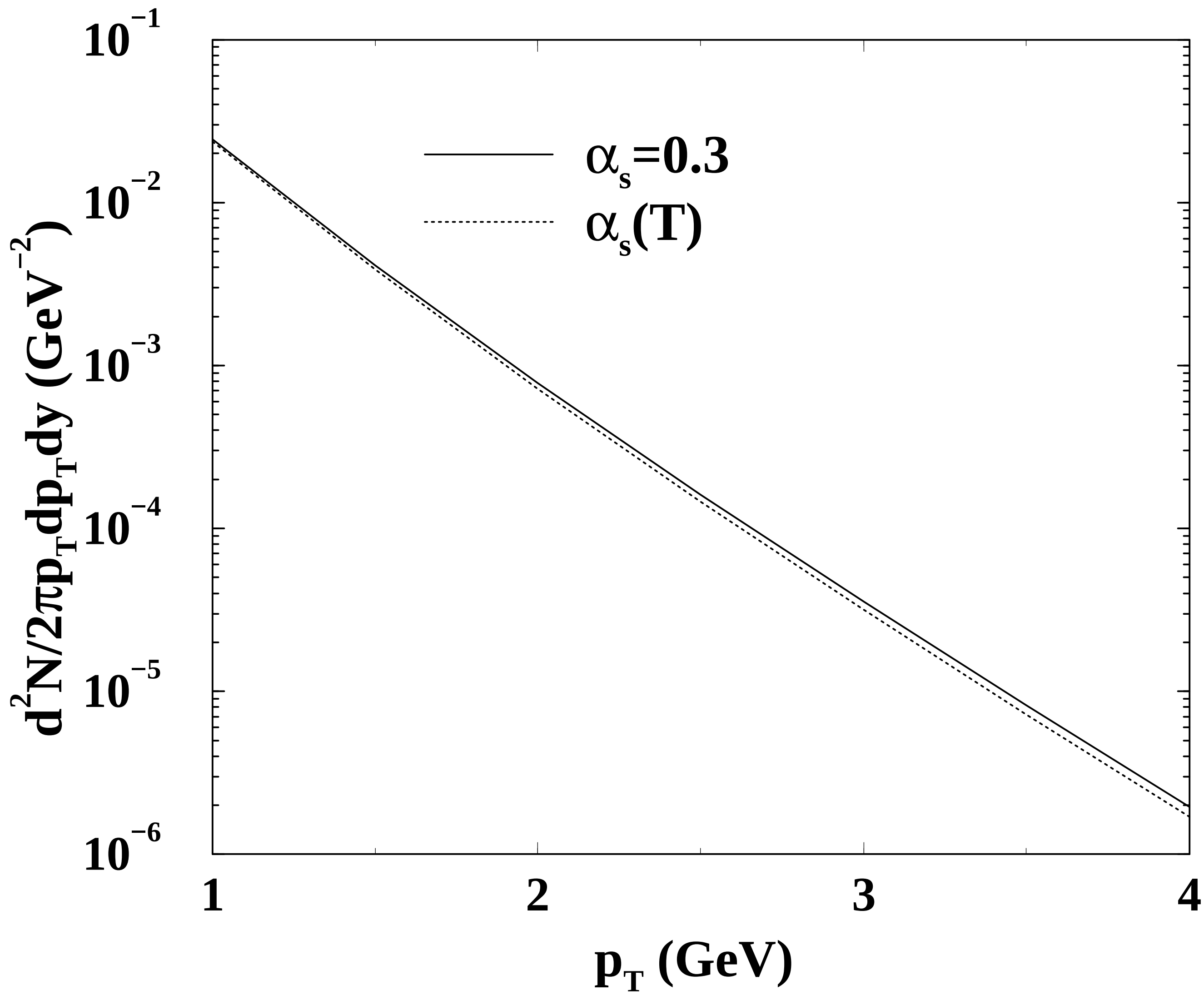

Figure 6. Photon emission from QGP phase for two values of strong coupling constant α_s. Solid (dotted) line indicates results for $\alpha_s = 0.3$ (temperature dependent coupling). Here $T_i = 400$ MeV, $\tau_i = 0.2$ fm and $T_f = 120$ MeV. Type I EOS has been used here.

215 MeV because the thermal photon spectra is a superposition of emission rates for all the temperatures from initial to freeze-out. This indicates that the temperature of the system formed after the collisions is higher than the transition temperature for deconfinement. The lower limit in the initial temperature can be used to put a conservative upper bound on the thermalization time, which in the present case is ~ 1.3 fm. The invariant mass distribution of lepton pairs in the similar framework will be reported shortly [71].

In spite of the encouraging situation described above it is worthwhile to mention the following. The experimental data [8] for real photon spectrum in $Au + Au$ collision has been obtained from the analysis of the low mass and high p_T lepton pairs by assuming

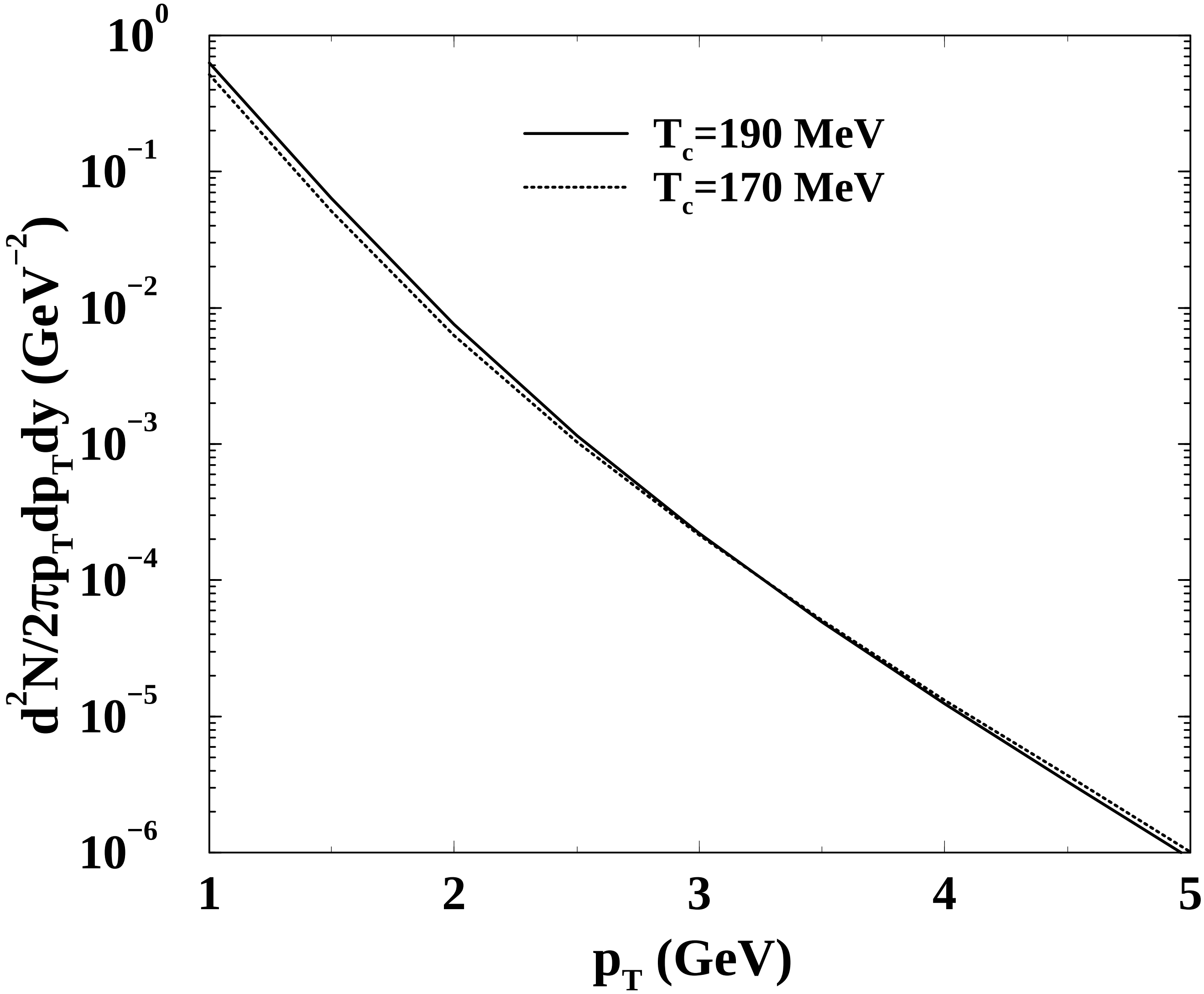

Figure 7. Photon emission from QGP phase for two values of transition temperature, T_c. Solid (dotted) line indicates results for $T_c = 190(170)$ MeV. Here $T_i = 400$ MeV, $\tau_i = 0.2$ fm and $T_f = 120$ MeV. Type I EOS has been used here.

$\gamma_{direct}/\gamma_{incl} = \gamma^*_{direct}/\gamma^*_{incl}$ ($*$ indicates virtuality). The similar procedure should be adopted for analysis of photon data for pp and $p(d) + Au$ collisions. Moreover, the data from pp and $p(d) + Au$ collisions for $1 < p_T$(GeV)< 5 at $\sqrt{s_{NN}} = 200$ GeV will be useful to validate the NLO pQCD contributions for $Au + Au$ collisions and hence will be helpful to quantify the thermal contribution.

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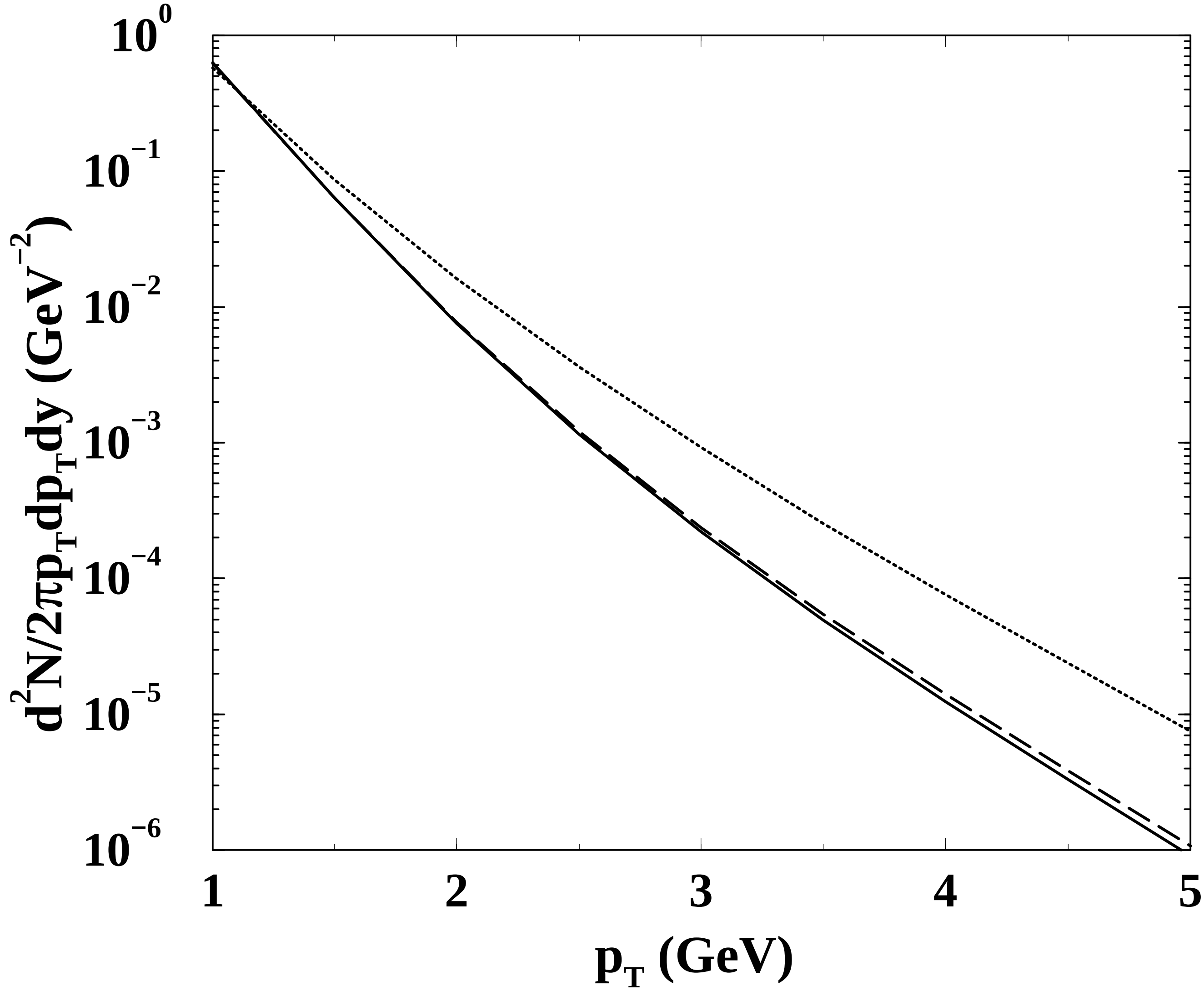

Figure 8. Thermal photon spectra with different initial velocity profile. Solid (dashed) line indicates results for $v_0 = 0(0.2)$ in Eq.4. Results for a different initial velocity profile $v_r(\tau_i, r) = v_0^1\, r/R_A$ with $v_0^1 = 0.2$ is also shown (dotted line). Here $T_i = 400$ MeV, $\tau_i = 0.2$ fm and $T_f = 120$ MeV. Type I EOS has been used here.

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